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PHASE I & II FINAL REPORT

VOLUME II
SUPPORTING RESEARCH AND TECHNOLOGY REPORT

SYSTEM TECHNOLOGY ANALYSIS OF AEROASSISTED ORBITAL TRANSFER VEHICLES: MODERATE LIFT/DRAG (0.75-1.5)

AUGUST 1985

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SUBMITTED TO

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FORWARD

This final report of the "System Technology Analysis of Aeroassisted Orbital Transfer Vehicles: Moderate Lift/Drag (0.75-1.5)" was prepared by the General Electric Company, Space Systems Division for the National Aeronautics and Space Administration's George C. Marshall Space Flight Center (MSFC) in accordance with Contract NAS8-35096. The General Electric Company, Space Systems Division was supported by the Grumman Aerospace Corporation as a subcontractor during the conduct of this study. This study was conducted under the direction of the NASA Study Manager, Mr. Robert E. Austin, during the period from October 1982 through June 1985.

The first phase of this program focused on a ground based AOTV and was completed in September 1983. The second phase was directed towards a space based AOTV and the cryofueled propulsion subsystem-configuration interactions and was completed in March of 1985. The second phase was jointly sponsored by NASA-MSFC and the NASA Lewis Research Center (LeRC). Dr. Larry Cooper was the LeRC study manager.

This final report is organized into the following three documents:

Volume IA	Executive Summary - Parts I & II
Volume IB	Study Results - Parts I & II
Volume II	Supporting Research and Technology Report
Volume III	Cost and Work Breakdown Structure/ Dictionary

Part I of these volumes covers Phase 1 results, while Part II covers Phase 2 results.

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VOLUME II - PARTS I & II

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VOLUME II

PARTS I & II

1.0 INTRODUCTION

Technology payoffs of representative ground based mid L/D AOTVs have been assessed and prioritized in Phase I of this study while represeentative space based mid L/D AOTVs have been examined in Phase II of this study.

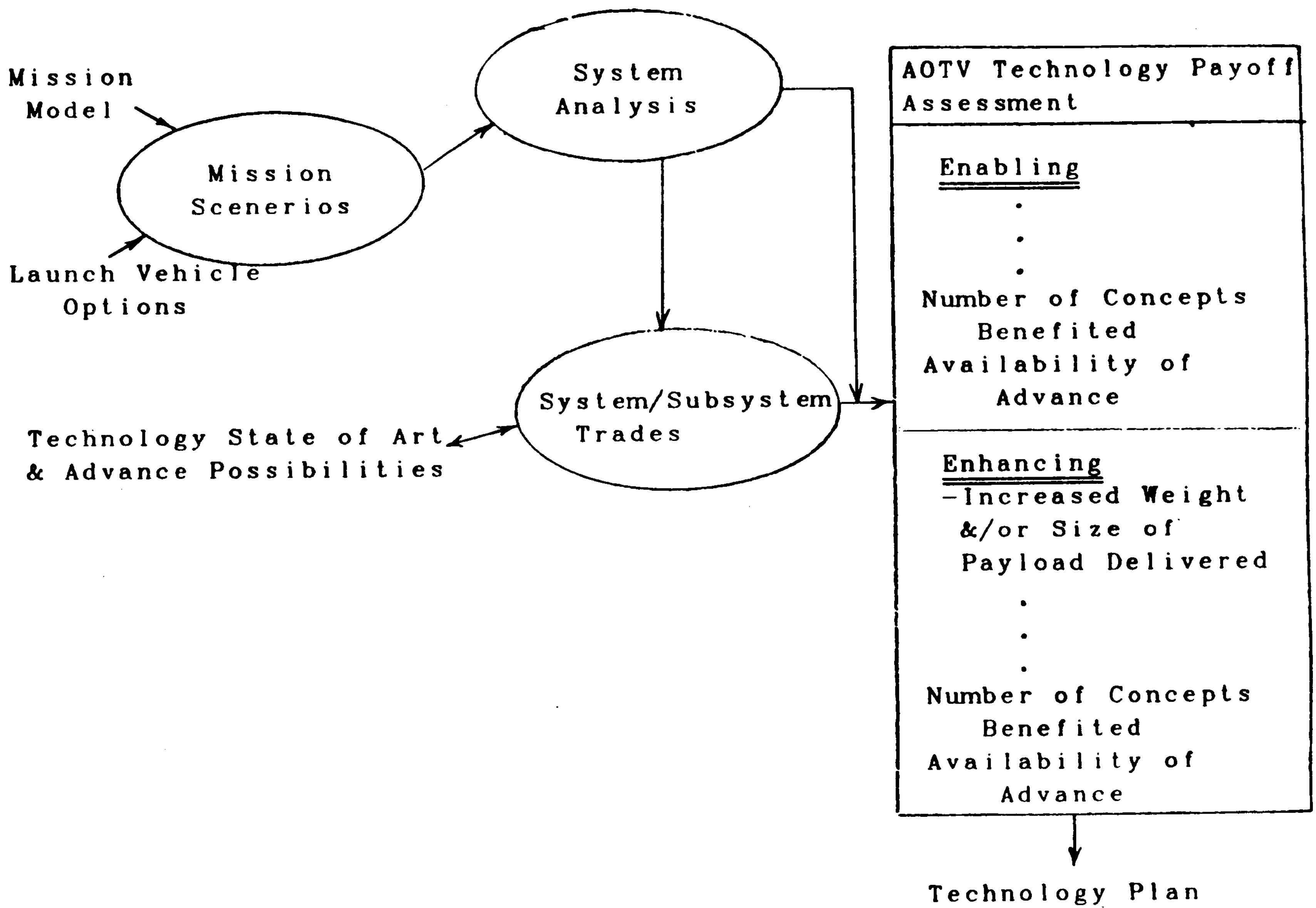
The major tasks of Phase I are outlined in Figure 1-1 and include four major areas: System Analyses, System/Subsystem Trades, Technology Payoff Assessment and Plan and Cost Analyses. The System Analyses task consists of broad configuration/concept trades, flight performance analyses, aerodynamics of configurations aeroheating and thermal protection system concepts, guidance, navigation, and control performance options, operations analyses and concept assessment. The System/Subsystem Trades task consists of evaluating the payoffs of technology advances in the areas of structures and materials, thermal protection materials and concepts, avionics, propulsion, and flight controls.

The Technology Assessment/Payoff task involves a definition of current state-of-the-art, specifying an assessment criteria, evaluating and ranking the technology payoffs, and generating a technology plan for each high payoff technology.

Phase II dealt with space based AOTVs and utilized the same major tasks as Phase I with one exception. The Propulsion System/Subsystem Trades task was expanded to evaluate in greater detail the cryofueled propulsion subsystem-configuration interactions.

The methodology employed to generate technology payoffs, the major payoffs identified, the urgency of the technology effort required, and the technology plans suggested are summarized in this volume for both Phases I and II of this study.

FIGURE 1-1. **SYSTEM TECHNOLOGY ANALYSIS OF MID L/D AOTV**



2.0 METHODOLOGY

A detailed review of the current state-of-the-art in the various technology and subsystems areas was conducted to serve as a baseline point of departure of this study, Figure 2-1. Technology advancement possibilities identified in numerous recent studies of OTV, AOTV, SDV and STS were reviewed. These results were compared with our in-house data base and parameters selected that represent improvements due to nominal expected growth resulting from normal funding of these technology areas. A number of these improvements resulting in from 10 to 70% reduction of subsystem weight are summarized in Table 2-1. Other improvements include such items as increase of maximum operating temperature of the thermal protection system elements, increased confidence in the hypersonic aerodynamic characteristics, and numerous others.

Various techniques exist for ranking the technology benefits. The method selected for the Phase I ground based portion of this study is as follows: given a subsystem weight reduction or other performance improvement possibility, the effect on increased payload weight was determined and this payload gain was converted to a customer cost benefit, given a nominal delivery cost to GEO of $8000 per lb. The technology benefits were then rank-ordered in decreasing magnitude of customer cost benefit.

In the Phase II space based portion of this study, a different approach was taken: The on-going Phase A AOTV studies have shown that 60-90% of the life cycle costs is composed of AOTV propellant transport cost to LEO. So, given a subsystem weight reduction or other performance improvement possibility, the effect on propellant transport cost savings to LEO was determined in a trending analysis. The technology benefits were then rank-ordered in decreasing magnitude of propellant transport cost savings.

In addition, during Phase II, an AOTV-payload manifesting study was conducted to evaluate the relative advantages/disadvantages of alternate storable propellants.

FIGURE 2-1. **CURRENT TECHNOLOGY STATE OF THE ART**

AERODYNAMIC ANALYSIS	HYPERSONIC ARBITRARY BODY PROGRAM, AFFDL-TR-73-159 INVISCID (3IT AND 3IS) FLOW FIELD CODES, SAMSO-TR-79-5 VISCOUS (3VFF) FLOW FIELD CODE, AFFDL-TR-78-67 PARABOLIZED NAVIER-STOKES CODE PLUS ASSOCIATED I/O GRAPHICS LaRC WIND TUNNEL DATA MK500 FLIGHT DATA BASE (CLASSIFIED)
AEROTHERMODYNAMIC ANALYSIS	VISCOUS (3VFF) FLOW FIELD CODE EQUILIBRIUM HOT GAS RADIATION, W.A.PAGE, AIAA 68-784 NON-EQUILIBRIUM HOT GAS RADIATION, NASA ARC BOUNDARY LAYER TRANSITION, NESTLER AND FLORENCE RECENT SURVEY

THERMAL PROTECTION SYSTEMS	REUSABLE: AFRSI, FRCI, RCC RERADIATIVE METALLIC PANELS TRANSPIRATION COOLING (TCNT AND GASJET) REFURBISHABLE ABLATIVES
STRUCTURE:	ALUMINUM, GRAPHITE COMPOSITES
ADHESIVES:	EPOXY AND SILICONE BASED
AVIONICS:	GPS, ADAPTIVE GUIDANCE
PROPULSION:	RL 10A-3-3A
FLIGHT CONTROLS:	RCS, TRIM FLAPS, BODY SLICES, BENT NOSE, MOVEABLE MASS

Table 2-1. **Technology Advancement Potential**

AOTV Subsystem Element	Expected Improvement
Structure (shell, frames, supports and flaps - Improved Design Allowables - New Materials	10 to 30% weight reduction
Thermal Protection System - Reduced Coating Weight - Non-catalytic Coatings - Increased Bond/Structure and maximum surface temperatures	Up to 56% weight reduction
Transpiration Cooled Nose	7^{o} plane change increase for 5X GEO return
Avionics - Degree of Autonomy/Redundancy	50 to 70% weight reduction
Electrical Power Supply - New Materials	20 to 38% weight reduction
New Cryofueled Engine - High Chamber Pressure - Mixture Ratio 6-7	Isp up to 480 seconds

3.0 MAJOR TECHNOLOGY ADVANCE PAYOFFS

3.1 Ground Based AOTV - Phase I

AOTV payload delivery sensitivities to various parameters such as vehicle dry weight, engine specific impulse, available lift/drag have been evaluated for representative mid L/D AOTVs and summarized in Figure 3-1. Note that the sensitivities are relatively independent of L/D in this range.

A large number of potential subsystem weight reductions have been identified, are discussed in detail in Volume IB, and summarized in Table 2-1.

The mid L/D AOTV payload delivery sensitivities of Figure 3-1 have been combined with the delivery cost and the subsystem weight reduction possibilities to generate the results summarized in Figure 3-2 for the 38 ft and OH-3 delivery vehicles. Note that the 38 ft single stage vehicle has very different technology payoffs from the small OH-3 perigee kick vehicle.

Additional technology advance benefits are summarized in Figure 3-3 for both vehicles. Aerodynamic uncertainties due to viscous and rarefaction effects will exist and could amount to as much as ± 0.1 of Δ L/D. This uncertainty requires a propellant contingency which in turn decreases the payload delivery capability. Flight vehicles have typically flown initially with a safety margin in the thermal protection system of as much as 25%. This translates into a very large payload loss (and hence cost benefit if it is decreased or eliminated) for the 38 ft delivery vehicle but a much smaller effect for the OH-3 vehicle due to its much smaller size. In the GN&C subsystem areas, the ability to obtain aerodynamic plane change is translated into payload gain and hence customer cost benefit. The value of an "optimum" guidance system that has been selected because it is capable of obtaining the most aerodynamic plane change from a given vehicle configuration is illustrated for one degree of incremental plane change. The value of an "Adaptive" guidance system that has the capability of updating during the early portion of entry is illustrated for each additional one degree of incremental plane change. The value of an "Adaptive" guidance system that has the capability of updating during the early portion of entry is illustrated for each additional one degree of plane change that can be generated. The effect of encountering a 30% density shear (pocket) similar to that experienced by a recent STS flight has been demonstrated to have no effect on a vehicle with L/D = 1.5 but to have a small effect on a vehicle with L/D = 0.6.

FIGURE 3-1. SUMMARY OF PAYLOAD DELIVERY SENSITIVITIES FOR A GROUND BASED SINGLE STAGE AOTV-65K STS

PARAMETER		MISSION	P/L SENSITIVITIES L/D = 0.75	1.5
AOTV DRY WEIGHT	$\frac{\Delta W_{P/L}}{\Delta WT_{DRY}}$ (LB/LB)	GEO DELY	-1.65	-1.65
		6 HR POLAR	-1.7	-1.5
ENGINE I_{SP}	$\frac{\Delta W_{P/L}}{\Delta I_{SP}}$ (LB/SEC)	GEO DELY	64	64
LIFT-DRAG RATIO	$\frac{\Delta W_{P/L}}{\Delta L/D}$ (LB)	GEO DELY	430	430
		6 HR POLAR	2000	1700
		GEO MANNED RT	800	800
PROPULSIVE PLANE CHANGE AT MISSION ALTITUDE	$\frac{\Delta W_{P/L}}{\Delta i_{PROP}}$ (LB/o)	GEO DELY	-34	-34
		6 HR POLAR	-183	-183

FIGURE 3-2

EFFECT OF SUBSYSTEM WEIGHT REDUCTION DUE TO TECHNOLOGY ADVANCES ON CUSTOMER COST BENEFIT

- GROUND BASED AOTV -

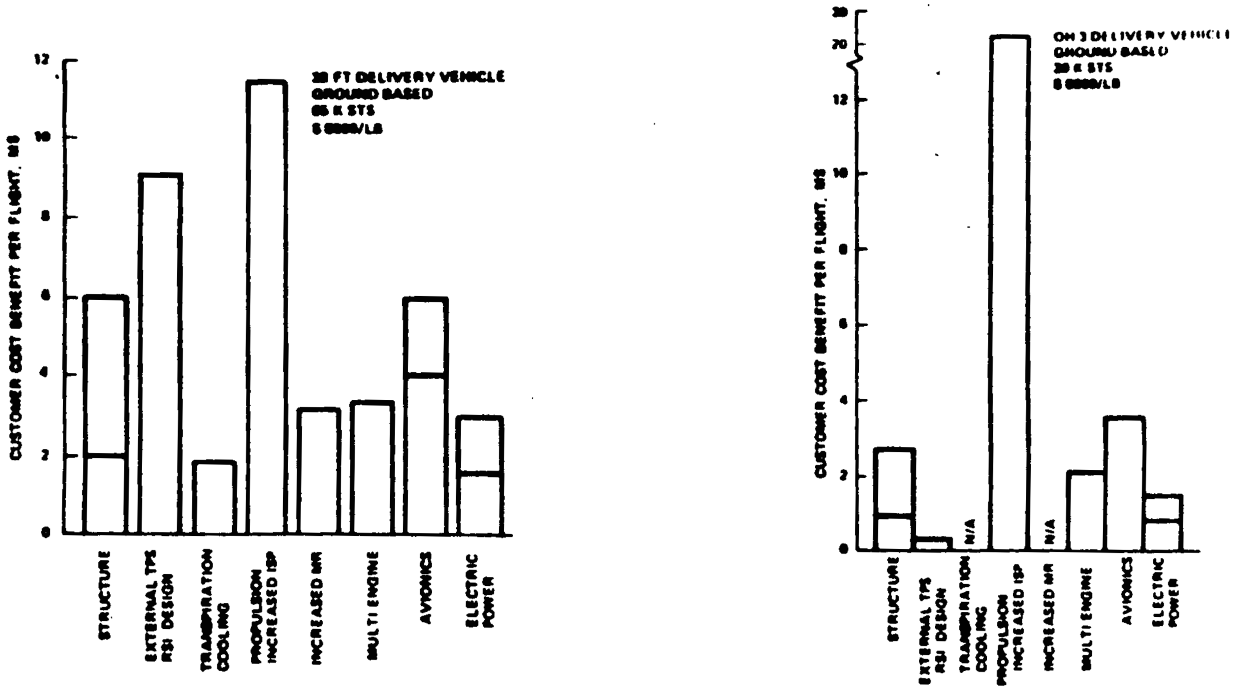
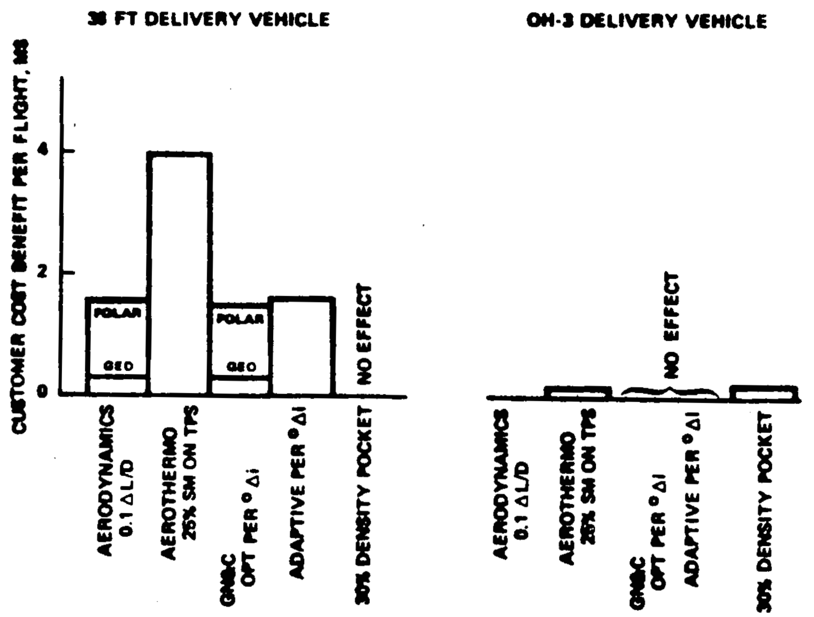


FIGURE 3-3

EFFECT OF TECHNOLOGY ADVANCES ON CUSTOMER COST BENEFIT



Some of the technology issues are more nebulous to quantify at this stage in the program but our best engineering judgment has been summarized in Table 3-1 as to the relative importance of these issues.

Considering all of the above, the recommended ground based AOTV Technology Priority order is summarized in Table 3-2

3.2 Space Based AOTV - Phase II

The effect of subsystem weight reduction and other performance improvements on the AOTV propellant transport cost to LEO have been evaluated and summarized in Table 3-3. Note that the recommended delivery mode of perigee kick + AKP provides cost sensitivities much different than the single stage delivery or manned round trip. This is due primarily to the much smaller perigee kick vehicle. The numerous potential subsystem weight reductions identified in Phase I of this study, summarized in Table 2-1, are still valid for this space based phase of the study (Phase II).

The mid L/D AOTV propellant transport cost sensitivities of Table 3-3 have been combined with the subsystem weight reduction possibilities of Table 2-1 to generae the propellant transport cost savings summarized in Table 3-4. In this comparison, the perigee kick vehicle has been used for 10 GEO delivery missions per year and a single stage vehicle used for 2 manned missions per year.

Additional technology advance benefits in the areas of improved aerodynamics and GN&C have been identified in the ground based Part I of this study, Section 3.1, and are still considered applicable here. The importance of some of the technology issues more nebulous to quantify, identified in Table 3-1 for the ground based mode, is still applicable for the space based mode.

In addition, during Phase II, an AOTV-payload manifesting study was conducted to evaluate the relative advantages/disadvantages of alternate storable propellants. Results of the AOTV-payload manifesting study indicated that on a performance basis: 1) for a ground based only system the storable propellant, N_2O_4/MMH, required fewer STS flights, 2) for a space based only or space based with ground based capability, the cryogenic propellant LO_2/LH_2 required significantly fewer STS flights. However, on the basis of a total cost estimate, including providing space basing capability, over a six year cost cycle, N_2O_4/MMH saved about $100M when compared with Lo_2/LH_2. It is recommended that this area be examined in greater detail.

Considering all of the above, the recommended space based AOTV Technology Priority order is summarized in Table 3-5.

TABLE 3-1. MID L/D AOTV TECHNOLOGY ISSUES

TECHNOLOGY ISSUE	RELATIVE IMPORTANCE: Important	Minor Impact	Ground Test or Analytical Simulations	Flight Test	Applicable DTR in Reference 1
Aerodynamics					
Atmospheric Rarefaction and Uncertainty Effects on AOTV Performance					
- Aero Plane Change Capability		X			
- Control Flap Effectiveness	X		X	X	A1,A2,A7
- Dynamic Performance During Atmospheric Exit	X			X	A1,A7,A6
Vehicle Aerodynamic Uncertainties	X		X	X	A1,A2,A3
Aerothermodynamics					
Impacts Max TPS Surface Temperatures					
- Atmospheric Rarefaction Effects	X		X	X	A5
- TPS Surface Finite Catalytic Effects	X			X	A4
- Equilibrium Hot Gas Radiation		X			
- Non-Equilibrium Hot Gas Radiation	X			X	A1,A4,A5
- Boundary Layer Transition of Large Axisymmetric Vehicles	X			X	A3
- Flap/Body Shock Interacting Flow-fields	X		X	X	A1,A2,A7
- Leeward Side Heat Transfer	X		X	X	
TPS					
Increased Allowable Maximum Operating Surface Temperatures	X		X		TPS1, APS2
Increased Maximum Allowable Structure-Bond Line Temperatures	X		X		TPS1,STR1
Coating Weight Reduction/Elimination	X		X		TPS,TPS2
Thermal Conditioning Prior to Entry	X		X		
Transpiration Cooled Nose Enables One Pass Capture	X		X	X	A2 TPS3
GN&C					
Optimum Guidance	X		X		NGC1
Adaptive Guidance	X		X		NGC2 NGC3
Atmospheric Density Uncertainties		X			
Vehicle Aerodynamic Uncertainties	X		X		
Low Cost, Low Weight Inertial Navigation & Attitude Reference Systems	X		X		NGC5

TABLE 3-2. GROUND BASED
MID L/D AOTV TECHNOLOGY PRIORITIES
PHASE I

MISSION ENABLING TECHNOLOGY - GROUND BASED	
NONE	
MISSION ENHANCING TECHNOLOGY - GROUND BASED	
PRIORITY	ITEM
1*	SMALL NEW ENGINE WITH INCREASED I_{SP} & MR
2	EXTERNAL TPS DESIGN
3	AVIONICS WEIGHT REDUCTION
4	AERODYNAMIC KNOWLEDGE
5	AEROTHERMODYNAMIC KNOWLEDGE
6	STRUCTURE WEIGHT REDUCTION
7	ELECTRICAL POWER SUPPLY WEIGHT REDUCTION

*PHASE II RESULTS INDICATE THAT STORABLE PROPELLANT ENGINES MAY BE MORE ATTRACTIVE

TABLE 3-3. SPACE BASED MID L/D AOTV PERFORMANCE SENSITIVITIES

	PERIGEE KICK	SINGLE STAGE	14K ROUND TRIP
$\frac{\partial (W_P + W_{AKP})}{\partial W_{DRY}}$ $(\frac{LB}{LB})$	0.73	2.8	2.9
$\frac{\partial W_P}{\partial I_{SP}}$ $(\frac{LB}{SEC})$	63.3		L/D = 0.75 1.5 290 293
NUMBER OF FLIGHTS IN MODEL	100	100	20
$\frac{\partial \$ \text{ PROP TRANSPORT}}{\partial W_{DRY}}$ $(\frac{\$}{LB})$	\$73,300	\$282,000	\$57,600
$\frac{\partial \$ \text{ PROP TRANSPORT}}{\partial I_{SP}}$ $(\frac{\$}{SEC})$	\$6.3M		\$5.8-5.86M

TABLE 3-4. SPACE BASED MID L/D AOTV TECHNOLOGY PAYOFFS

(IN ORDER OF IMPORTANCE)

INCREASED I_{SP} (480 VS 443)	\$451M
AVIONICS WEIGHT REDUCTION	\$44-61M
EXTERNAL TPS DESIGN	\$ 45M
ELE TRICAL POWER SUBSYSTEM WT REDUCTION	\$18-33M
STRUCTURE WEIGHT REDUCTION	
IMPROVED ALLOWABLES + NEW MATERIALS	\$ 9-26M
SPACE BASED VS GROUND BASED	\$35M

- ASSUMES PROPELLANT TRANSPORT COST OF \$1000/LB TO LEO
  100 GEO-DELIVERY + 20 MANNED ROUND TRIP FLIGHTS

TABLE 3-5

SPACE BASED MID L/D AOTV TECHNOLOGY PRIORITIES

PHASE II

MISSION ENABLING TECHNOLOGY - SPACE BASED

AUTOMATION OF ROUTINE INSPECTION & MAINTENANCE

MISSION ENHANCING TECHNOLOGY - SPACE BASED

PRIORITY	ITEM
1	IMPROVED LIFE TIME OF STORABLE PROPELLANT ENGINE
2	AVIONICS WEIGHT REDUCTION + GN&C
3	EXTERNAL TPS DESIGN
4	AERODYNAMIC KNOWLEDGE
5	AEROTHERMODYNAMIC KNOWLEDGE
6	ELECTRICAL POWER SUBSYSTEM WEIGHT REDUCTION
7	STRUCTURE SUBSYSTEM WEIGHT REDUCTION

4.0 TECHNOLOGY PLAN

The cost benefits of technology advances for several different ground based and space based vehicle concepts have been evaluated across the L/D range of 0.75 to 1.5. It was determined that within the mid L/D range, the benefits were nearly independent of L/D but single stage vehicles (38 ft delivery vehicle) and stage and a half vehicles (H-1M) exhibit much different cost benefits than the OH-3 perigee kick type vehicle, Figures 3-2 and 3-3. In general, the large 38 ft delivery vehicle benefitted more from those technology advances that produced smaller or lighter AOTV subsystems, such as smaller propellant tanks, lighter TPS, or vehicle structure. The two different vehicle classes did share a common benefit from increased propulsive specific impulse. The recommended orders of priority for the ground and space-based AOTV Technology programs have been summarized in Tables 3-2 and 3-5.

A survey was conducted of NASA LRC, JSC, and ARC in October of 1984 to ascertain their perceptions of AOTV Technology Needs. The 1982 Aeroassist Working Group Technology development Plan was used as a basis for discussing their current R&T Programs and Plans in a series of working meetings at the various centers. As a result of this series of meetings, an updated draft version of the AOTV Technology Development Plan was generated and a list prepared of those Technology Areas perceived to need supplemental emphasis/funding, Table 4-1.

Many of these technology issues can be dealt with employing analytical/numerical simulations as well as ground tests in existing facilities. The current status of these technology areas, the justification for AOTV advocacy/ sponsorship, the objective, approach and resource requirements of the proposed efforts are detailed in Appendix A.

Many of the technology development areas identified as high payoff in this mid L/D AOTV study can best be supported by implementation of a number of experiments on a hypersonic entry flight test vehicle. A study was conducted in 1979-80 under Contract NAS-9-15977 that surveyed the U.S. hypersonic community to secure an estimate of the then current state-of-the-art of those technologies of interest for NASA and DoD space missions of the 1985-2000 time period. AOTV was included in that survey. Forty individuals and/or organizations were contacted and asked to comment on an assessment prepared by the SLRV study contractor. Twenty-one responded with comments and additional inputs for areas not included in the initial assessment.

The composite assessment, in the form of Detailed

TABLE 4-1

TECHNOLOGY AREAS NEEDING SUPPLEMENTAL FUNDING

	NEW INITIATIVE REQUIRED	AUGMENT ON-GOING PROGRAM
- DEVELOPMENT OF LESS CATALYTIC THERMAL PROTECTION MATERIALS COATINGS	X	
- TPS/STRUCTURAL DESIGN - EVALUATE NEW STRUCTURAL MATERIALS AND BOND SYSTEMS OPERATING AT HIGHER SOAK OUT TEMPERATURES	X	X
- DESIGN, FABRICATE AND TEST TRANSPIRATION COOLED NOSE WITH SEEDED COOLANT	X	
- AEROTHERMODYNAMIC METHODOLOGY - LEESIDE AND BASE AREA HEAT TRANSFER AND WAKE CLOSURE		X
- AERODYNAMICS - CONTROL FLAP EFFECTIVENESS		X
- AUTOMATION OF INSPECTION AND ROUTINE MAINTENANCE	X	
- PAYLOAD MANIFESTING ACROSS MISSION MODEL TO EVALUATE CRYO VS. STORABEL PROPELLANT TRANSPORT ADVANTAGES/DISADVANTAGES	X	
- GN&C - OPTIMIZATION OF A HYBRID FLIGHT CONTROL MECHANISM THAT BLENDS THE AERODYNAMIC AND REACTION CONTROL SUBSYSTEMS ON A LIFT MODULATED AOTV		X
- GN&C - DEVELOPMENT OF ADAPTIVE OPTIMAL STEERING LAWS		X
- AVIONICS - EVALUATION OF INERTIAL INSTRUMENT DEVELOPMENT AND PERFORMANCE, PROVIDE DIRECTION TO INSTRUMENT CONTRACTORS		X
- ELECTRICAL POWER SUBSYSTEM WEIGHT REDUCTION		X
- N_2O_4 - MMH ENGINE NOT EVALUATED DURING THIS STUDY		
- MANUFACTURING METHODS FOR LOW COST DROP TANKS	X	
- STRUCTURAL HEALTH MONITORING	X	

Technology Requirements, was published originally, Reference 1. That assessment has been reviewed and those DTRS selected that are pertinent to the mid L/D AOTV. A listing is presented in Table 3-1 that indicates which AOTV technology need is addressed by the varous DTR's of Reference 1.

Flight test objectives, measurements required, flight test conditions and major concerns have been detailed for the above technology requirements during the conduct of Contract NAS-9-15977 and have also been published in Reference 1.

5.0 REFERENCES

1. Jamison, C., et al, "Shuttle Launched Research Vehicle Applications and Benefits Study", Volume II, Flight Program Development, NASA CR-161019, 15 June 1981.

APPENDIX A

MID L/D AOTV SUPPORTING TECHNOLOGY PLANS
FOR GROUND AND SPACE BASED VEHICLES

PHASES I & II

PROPULSION SUBSYSTEM

Title: Propulsion Technology Development of Advanced Expander Engines

Status: The advanced OTV propulsion system program currently underway at NASA LeRC has a goal of improving the specific impulse of reusable LOX-H_2 fueled engines. A goal of 480 to 490 seconds appears within reach.

Justification: The increased specific impulse provides large increases in AOTV payload delivery capabiilty and hence a large customer cost benefit. In the cases examined, increase of Isp from 443 to 480 seconds resulted in the largest cost benefit of any technology advanced examined. For a ground based AOTV the customer cost benefit was $115M/flight. For a space based AOTV, the propellant transport cost benefit over a ten year period is $451M.

Objective: Develop the engine technology for eventual production of a small LOX-H_2 fueled advanced expander engine with thrust range in the 2 to 4 K lb range and an I_{sp} in the range of 480 to 490 seconds.

Technical Approach: Conduct design studies component development, and tests in the areas of

- Increased turbine speeds
- High expansion ratio nozzles
- Gaseous oxygen flow

Resource Requirements: OAST should continue funding advanced OTV propulsion system technology development at NASA LeRC.

THERMAL PROTECTION SYSTEM

Title:	Less Catalytic TPS Coating Material Candidates
Status:	Current Shuttle Orbiter experiments have demonstrated some heat transfer reductions from the fully catalytic values for the current TPS coating materials.
Justification:	AOTV flies in a more rarefied regime than the Orbiter, and is expected to experience larger hypersonic heating reductions due to the non-catalytic nature of the TPS coatings. If the TPS coatings could be made even less catalytic, additional heating reductions would occur. Reductions of peak TPS surface temperatures expected range from 500 to 1200°F from the fully catalytic values. Realization of reductions of this magnitude would enable some missions that otherwise were tempeature constrained or allow significant TPS mass reduction.
Objective:	Identify potential coatings for AOTV TPS that are less catalytic and therefore may further reduce the hypersonic heat transfer experienced.
Technical Approach:	Conduct a thorough literature search (including Russian) in the areas of: 1) Atom recombination and the effect of coating surfaces on recombination. 2) Radiative energy release by excited diatoms that have been formed by atoms recombining on the surface. 3) Luminescense Select and review signficiant papers in the above areas. Identify potential coating possibilities for AOTV applications.
Resource Requirements:	A recommended new initiative

	FY 86	87	88
Manpower (yrs)	0.5		
Specialized Facilities	None		
Funding ($K)	47.0		

AVIONICS SUBSYSTEM

Title:	Evaluation of Inertial Instrument Development Status and Performance
Status:	Estimates of the weight, power requirements and performance of the inertial instruments used in current estimates of AOTV weight and performance are based upon contemporary electromechanical devices of Shuttle Orbiter heritage.
Justification:	The continued investment by the principal sources of inertial instruments, Delco, Honeywell, Litton and Singer, results in the steady progress towards improved accuracy with smaller components and reduced power requirements, i.e., ring laser/resonant gyro. A continuous interaction with these suppliers is needed to ensure that AOTV forecasts reflect the latest advances and to provide guidance to them so that their development reflect AOTV requirements. It has been projected that avionics subsystem weight reductions of 50 to 70% may be possible. This translates into a $4 to 6M/flight customer cost benefit for ground based AOTVs or $44 to 61M propellant transport cost benefit over a ten year period for space based AOTVs.
Objective:	The objective of this task is to establish an interaction with the principal sources of inertial instruments that will ensure that the AOTV program is current with respect to instrument developments and provides support and guidance to the instrument contractors.
Technical Approach:	Work statements will be prepared and specifications developed for instruments suitable for the AOTV application. This will be accompanied by performance analyses and the joint (GE-Subcontractor) evaluation of the performance of sample hardware using our dynamic facilities.
Resource Requirements:	Augment on-going programs

FY	86	87	88
Manpower (yrs)	1	1	1
Funding ($K)	350	350	350

AVIONICS SUBSYSTEM

Title:	GN&C - Optimization of a hybrid flight control mechanization that blends the aerodynamic and reaction control subsystems of a lift modulated AOTV to secure the desired performance for a minimum weight.
Status:	The use of both a split windward flap flight control subsystem and a reaction control subsystem for AOTV missions has been studied and proposed in mission studies for NASA MSFC, JSC and JPL. However, this concept has never been optimized for minimal weight of the combined subsystem.
Justification:	Reducing the weight of the AOTV flight control subsystem has a direct impact on payload capability. For example, if 50% of the flap control system mass could be eliminated through this optimization task, it would translate into $1.5M/flight of customer cost benefit for ground based GEO delivery AOTVs or into $14.7M in decreased propellant transport costs over a 10 year flight program for a space based system.
Objective:	Reassess the implementation of the aero flap reaction control subsystems, utilizing recent information on flap effectiveness to minimize the combined weight of these elements.
Technical Approach:	The recent development of flow field techniques to assess the influence of vehicle size on flap control effectiveness suggests that the AOTV configurations should be reassessed. The study would demonstrate the flap size and duty cycle which best complement the use of the reaction control subsystem needed for the high roll rate requirements at entry and exit from the earth's atmosphere. Parametric studies will be performed to establish a least weight hybrid subsystem for a representative mid L/D AOTV configuration.

Resource Requirements: Augment on-going Program

	FY 86	87	88
Manpower	1.0		
Specialized Facilities	None		
Funding ($K)	150		

AVIONICS SUBSYSTEM

Title:	GN&C - Development and Evaluation of Optimal (fuel conservative) Strategies for transfer from GEO to either coplanar or cross-plane LEO for lift modulated configurations using adoptive in-atmosphere guidance.
Status:	Development and demonstration of adaptive guidance algorithms for optimal in-atmosphere transfer between coplanar orbits is underway at NASA JSC, LRC and JPL.
Justification:	Obtaining maximum plane change capability from a mid lift/drag AOTV, given some errors in position and velocity, has a significant cost benefit. For example, the customer cost benefit for single stage GEO return is $1.6M per flight for each degree of plane change that the adoptive guidance system delivers.
Objective:	Continue to develop, refine and demonstrate improved in-atmosphere guidance algorithms with the goal of obtaining the maximum aerodynamic plane change possible in the presence of a nominal atmosphere.
Technical Approach:	The AOTV problem will be established as a formal approach to optimize plane change capability. The sensitivity of optimization methods to off nominal conditions will be minimized by performing the optimization calculations in a real time frame from available measurements. The sensitivity to measurement error will be minimized by the use of second variation optimization methods with terminal constraints. This technique has been used in previous re-entry guidance studies for bank-to-turn vehicles, and has advantages over the first and parameter optimization techniques. The second variation technique provides a nominal history, as well as a set of gains needed to fly this trajectory. The computation convergence parameters and algorithms have been incorporated into our second variation technique and has been successfully used in our bank-to-turn studies.
Resource Requirements:	Augment on-going Program

	FY 86	87	88
Manpower (yrs)	1.0		
Funding ($K)	150		

AERODYNAMICS

Title:	Control Flap Effectiveness
Status:	Flight experience with the Shuttle Orbiter has demonstrated much different control flap effectiveness than had been predicted preflight based on the extensive ground test program conducted.
Justification:	Mid L/D AOTV employs a non-coordinated bank to turn steering scheme that employs a hybrid aero control surface - hot gas altitude control system.

Apriori knowledge of control flap effectiveness is necessary for proper flap sizing and ground simulations of the hybrid control system.

It has been estimated that a 50% uncertainty in size of the control flap required may exist. If this uncertainty were factored into an AOTV design as a heavier control flap, it would translate into $1.5 million/flight in lost revenues for a ground based system or into $14.7 million in increased propellant transport costs over a 10 year flight program for a space based system.

Objective: To experimentally measure AOTV control flap effectiveness for four different AOTV configurations and two different sized flaps for $M_\infty \geq 10$, laminar flow, near continuum flow.

Technical Approach: Conduct a series of hypersonic tunnel tests

- o Select two AOTV configurations.
- o Design each model with common frustum, two noses, and several size flaps and fabricate 2 configuration x 2 noses each x 2 sizes flaps = 6 separate configurations
- o Run tests at α_T for (L/D) max and β = 0, 5, 10° at $M_\infty \geq 10$
- o Evaluate data - compare to best predictions

Resource Requirements: Augment on-going programs

	FY 86	87	88
Manpower	1.5	3.0	1.5
Specialized Facilities	Hypersonic Wind Tunnel		
Funding (K$)	200	400	200

Title:	Vehicle Aerodynamic Uncertainties
Status:	Flight experience with the Shuttle Orbiter has demonstrated necessity of correctly accounting for the rarefied flow effects in the definition of the aerodynamic characteristics.
Justification:	Ultimate payload delivery capability and hence initial configuration selection is dependent on AOTV L/D and other aero characteristics. It is necessary to minimize the uncertainty in the aero characteristics for a given configuration as early as practical. For example, an L/D uncertainty of 0.1 is not unusual. Eliminating that uncertainty translates into a customer cost benefit for a single stage ground based AOTV of $0.34M per flight.
Objective:	Through a combination of analyses with robust flow simulation codes and hypersonic wind tunnel-shock tunnel tests, establish an AOTV aerodynamic characteristics data base for two mid L/D AOTV configurations.
Technical Approach:	Select two AOTV configurations. Generate 6DOF aerocharacteristics employing robust flow field codes Conduct a series of hypersonic tunnel tests - evaluate effects of Reys, M_{∞}, $M_{\infty}/\sqrt{Re_{\infty}}$

Resource Requirements: Advocate Continuation of On-going Programs

	FY 86	87	88
Manpower	1.5	3	1.5
Specialized Facilities	Hypersonic wind tunnel and shock tunnel		
Funding ($K)	200	400	200

Title: Atmospheric Rarefaction Effects

Status: Activity is underway to bring on line robust flow field computer codes to better predict in the near-continuum flow regime the hypersonic entry environment. Some early calibration of these codes has taken place employing Shuttle Orbiter data.

Justification: The AOTV experiences all of its hypersonic heating at altitudes well above the primary area of interest for the Orbiter. The selection of TPS materials, the weight of the TPS and ultimately the AOTV configuration selected are all dependent on apriori prediction of the hypersonic heating over the vehicle - including the leeward side.

A thermal protection system safety margin of 25% is typical of that used to account for the numerous uncertainties in the design process, including rarefaction effects. Minimizing these uncertainties and thus the required TPS safety margin results in a potential customer cost benefit for a ground based AOTV of $4M. A 5 per flight for single stage GEO delivery to $250K per flight for perigee kick GEO delivery.

Objective: To provide continued improvement of capability of robust computer codes to predict the hypersonic heat transfer in rarefied, non-equilibrium flow fields and to experimentally measure the heat transfer distribution (including the leeward side) on representative AOTV configurations in these flow regimes to validate the new and improved codes.

Technical Approach:
- Continue development of Monte Carlo capability.
- Continue development of non-equilibrium flow numerical simulation.
- Continue development of PNS flow simulations
- Conduct a series of shock tunnel tests on representative AOTV configurations in these flow regimes
- Compare test to analytical results

Resource Requirements: Augment on-going programs

	FY 86	87	88
Manpower	6.5	7.0	2.0
Specialized Facilities	Hypersonic wind tunnel and shock tunnel		
Funding ($k)	1,000	1,100	300

Title:	AOTV Structural Health Monitoring
Status:	Monitoring of acoustic emission (AE) is currently employed as a method to determine impact damage on operational aircraft in Austrailia and Canada. AE is also being used in aircraft static tests and in composite structures static tests to predict failure loads accurately.
Justification:	To alleviate astronaut work load at the Space Station, the task of routine structural inspection of an AOTV can be delegated to a relatively inexpensive, lightweight AE system incorporated into the AOTV. Physical inspection by an astronaut would be required only when damage is sensed. Astronaut inspection time would be greatly reduced by knowing location of the damage.
Objective:	To determine structural behavior and sounds produced when experiencing hypervelocity impacts and to develop methodology for locating damage site.
Technical Approach:	Conduct hypervelocity impact tests while using AE to monitor sounds produced. Use linear or phased arrays of ultraonsic detectors to monitor impact/damaged region. Develop algorithms for use in triangulation process to locate damaged area.

Resource Requirements: A Recommended New Initiative

FY	86	87	88
Manpower	1.5	3.0	1.5
Specialized Facilities			
Funding	200	400	200

Title:	New Structural Materials Development
Status:	Development of new structural materials such as metal composites and aluminum lithium alloys is underway.
Justification:	Ultimate payload delivery capability of the Mid L/D AOTV is very dependent on AOTV dry weight. Any reduction of structural or TPS weight will have a major impact on reduction of AOTV dry weight. Recent design studies on AOTVs suggest utilization of these advanced materials and operating at maximum temperatures of 600 to 1000 °F enable a reduction of TPS mass with no increase in structural weight.
Objective:	Develop advanced structural materials with higher operating temperature capability and higher specific strength and stiffness.
Technical Approach:	Develop new metal matrix composite materials tailored for AOTV application in the areas of: o Boron/Al o SiC/Ti Screen these materials in standard laboratory tests. Provide preliminary specifications for manufacturing scale up.
Resource Requirements:	A recommended new initiative

FY	86	87	88	
Manpower (m years)	54	54	54	3 teams each working on 3 material concepts = 9 teams total
Specialized Facilities	Unidentified at this time			
Funding (M $)	6	6	6	

Title: Manufacturing Methods for Low Cost Drop Tanks

Status: Cryo stretch form technology has been demonstrated in aluminum which is preferred for these tanks. However, only spheres and cylinders with hemispherical ends have been built and these in small sizes. The space efficient ellipsoids and torroids have not been fabricated in low cost/high strength materials.

Justification: For space based AOTVs, over a ten year period, utilization of a perigee kick delivery vehicle (100 flights) and added drop tanks for the manned missions (20 flights) results in a propellant transport cost benefit of $1.25B when compared to using an off-loaded manned vehicle for delivery (in single stage mode) and a fully loaded manned vehicle for the manned missions.

Objective: Develop manufacturing methods for low cost, cryo stretch formed drop tanks.

Technical Approach:

- Determine plastic deformation characteristics of several preform shapes
- Verification of vessel shape and strength
- Verification of welding techniques for min gauge structures
- Verification of strength degradation at hardpoints

Resource Requirements: A Recommended New Initiative

FY	86	87	88
Manpower (m years)	10	10	
Specialized Faclities	Unidentified at this time		
Funding	$1M	$1M	

Title:	Design Allowables/Failure Criteria for Currently Available Graphite Composites
Status:	An organized activity is underway, spearheaded by the "AIAA Composite Structure Subcommittee" composed of members from NASA, Government agencies, and manufacturing firms. Their recent survey revealed composite structure design allowables were obtained from a wide variety of test methods and many different failure criteria were employed. The committee is striving for: 1) Unified testing to determine allowables - consensus is to use uniaxial data and analysis to determine composite properties. 2) Unified failure criteria for design of composite structure.
Justification:	Ultimate payload delivery capability of the mid L/D AOTV is very dependent on AOTV dry weight. It has been projected that 10 to 30% structure weight reduction may be possible with statistical improvement of the design allowable properties. This translates into a $1-6M customer cost benefit per flight for ground based AOTVs or $9-26M propellant transport cost benefit over a 10 year period for space based AOTV's.
Objective:	Through a combination of ground test and analyses execute a unified testing program to determine design allowables and develop a unified failure criteria.
Technical Approach:	Advertise AOTV as being a major advocate of the organized effort identified in "Status" above.
Resource Requirements:	No incremental funding requirements - major programs are underway under sponsorship of various military departments, DARPA, DNA, and NASA LRC. AOTV advocates continuation of these ongoing programs.

ELECTRICAL POWER SUBSYSTEM

Title:	Reduced Weight of Electrical Power Subsystems
Status:	Our state-of-the-art reference electrical power subsystem is a derivative of the Shuttle Orbiter and weights about 600 lbs.
Justification:	Ultimate AOTV payload delivery capability (weight and length) are very dependent on the AOTV dry weight and hence the electrical power subsystem weight. It is projected that 20 to 38% weight reduction may be possible by incorporation of non-metallic materials. This translates into a $1.7 to 3.2M/flight customer cost benefit for ground based AOTVs or $18 to 33M/flight propellant transport cost benefit over a ten year period for space based AOTVs.
Objective:	Through a combination of analytical and experimental development activities design, fabricate and demonstrate the incorporation of such non-metallics as graphite in the power section of the fuel cell to replace magnesium and nickel and continue to reduce the weight of the backup batteries.
Technical Approach:	The NASA OAST sponsored "NASA Regenerative Fuel Cell Program" at JSC and Lewis has this task in their program but unfunded. It is recommended that AOTV become an advocate for task funding.
Resource Requirements:	Augment on-going programs

THERMAL PROTECTION SYSTEM

Title:	Transpiration Cooled Nose Demonstration
Status:	Other DoD programs have developed, tested, and flown transpiration cooled noses for use in the turbulent continuum flow regime.
Justification:	The mid L/D AOTVs exhibit maximum nose surface temperatures during entry beyond the reach of even tomorrow's expected developments in reusable carbon-carbon system. Utilization of a transpiration cooled nose would enable many missions that currently are not possible or are seriously constrained due to material temperature limits.
Objective:	To provide design fabrication and aerothermal performance demonstration of a near full scale nose cap in a simulated hypersonic entry envioronment, in as rarefied flow state as feasible with existing test facilities.
Technical Approach:	Conduct a series of Plasma Arc Tests in simulated entry environments on a candidate AOTV transpiration cooled nose, demonstrating performance first at moderate temperatures and finally at temperatures consistent with its expected maximum operating capability.
Resource Requirements:	A recommended new initiative

FY	86	87	88
Manpower (yrs)	1.5	1.5	1.5
Specialized Facilities	Large Plasma Arc Test Facilities		
Funding ($K)	400	200	200

Title: Increased Maximum Allowable Structure Bond Line Temperature

Status: Current Shuttle Orbiter maximum design temperature of 350° can occur at landing when maximum TPS loads occur. AOTV loads at thermal soak out are expected to be small.

Justification: Increased maximum allowable structure-bondline temperatures allow a substantial reduction of the thermal protection system mass. Increasing the allowable to 600°F for a ground based AOTV, translates into a 37% TPS weight reduction potential. For GEO delivery missions this results in a potential customer cost benefit of $6M/flight.

Objective: To provide multicycle demonstration of increased maximum allowable structure-bondline temperatures.

Technical Approach: Conduct a series of thermostructural response tests under simulated worst case structural loading in a radiation heated facility. Tests should be conducted by two different teams. Assume two new material/bond/structure combinations per year for the next three years.

Resource Requirements: Advocate continuataion of on-going programs

FY	86	87	88
Manpower (yrs)	1.5	1.5	1.5
Specialized Facilities	High Temperature Radiant Test Facilities		
Funding ($K)	200	200	200

Title:	Thermal Conditioning Prior to Entry
Status:	Current Shuttle Orbiter TPS can be cold soaked prior to entry to reduce the maximum structure-bondline temperatures and hence improve the cross range capability.
Justification:	Cold soak thermal conditioning of AOTV TPS materials provides a substantial performance improvement. Cold soaking the TPS to -100°F prior to entry translates into a 23% TPS weight reduction potential. For GEO delivery missions this results in a potential customer cost benefit of $3.7M/flight.
Objective:	To provide multicycle demonstration of TPS cold soak thermal conditioning and subsequent entry thermal response under simulated structural loading.
Technical Approach:	Combine these test objectives with those for increased maximum allowable structure bondline temperature and cold soak the models first.

Resource Requirements:

- o Manpower (years) — Advocate continuation of on-going programs
- o Specialized Facilities — Included in Page A17
- o Funding

Title:	Development of Advanced Thermal Protection System Materials
Status:	Acc/RSI/FRCI/Advanced Ceramic material developments continue to take advantage of new fibers and composite fabrication techniques to produce stronger more durable materials at thermal efficiencies comparable to current materials and capable of higher use temperatures.
Justification:	Higher allowable operating temperature, lighter coating systems and improved non-catalytic coatings of reusable ceramic type materials provides an AOTV payoff of more aerodynamic plane change capability or lighter TPS and hence increased payload delivery capability or control margins. It is projected that TPS mass savings of up to 56% may be possible. This translates into a$0.5 to $11M customer cost benefit per flight for perigee kick and single stage ground based GEO delivery or $45M propellant transport cost benefit over a 10 year period for space based AOTVs.
Objective:	Develop advanced ACC/RSI/FRCI thermal protection materials with the goals of: o Higher allowable operating surface temperatures o Reduced coating weights o Improved non-catalytic nature of coating
Technical Approach:	Develop new material candidates by taking advantage of new fibers and composite fabrication techniques. Screen these material candidates in standard laboratory tests. Fabricate samples for the plasma arc/radiant heating develoment tests. Provide preliminary specification for manufacturing scale up.
Resource Requirements:	Advocate continuation of on-going programs

	FY 86	87	88
Manpower (yrs)	2.5	3.5	3.0
Specialized Facilities	Thermal test facilities at ARC, JSC and LaRC		
Funding ($K)	560	660	570

Title:	Increased Allowable Maximum Operating Surface Temperatures of New and/or Modified Ceramic Materials
Status:	RSI/FRCI/Advanced Ceramic material developments continue to take advantage of new fibers and composite fabrication techniques to produce stronger more durable materials at thermal efficiencies comparable to current materials and capable of higher use temperatures.
Justification:	Higher allowable operating temperatures of reuseable ceramic type materials provides an AOTV payoff of more aerodynamic plane change capability and hence increased payload delivery capability or control margins. Realization of higher allowable operating temperatures would enable some missions that otherwise were temperature constrained and allow its usage in a higher temperaure surface area where otherwise a higher density and hence heavier material was previously used.
Objective:	To provide multicycle demonstration of the maximum operating temperature for which the new material can be certified.
Technical Approach:	Conduct a series of plasma arc tests in simulated entry environments on the candidate new materials. Tests should be conducted by at least two different investigation teams. Assume two new materials per year for the next three years.
Resource Requirements:	Advocate continuation of on-going programs

	FY 86	87	88
Manpower (yrs)	1.5	1.5	1.5
Specialized Facilities	Plasma Arc Test Facilities		
Funding ($K)	200	200	200

Title:	TPS Coating Weight Reduction/Elimination
Status:	Current Shuttle Orbiter requires heavy ceramic coating over RSI for rainproofing on pad, 2) physical protection of RSI, 3) RSI sealing to prevent flow through during entry due to local pressure gradients.
Justification:	AOTV may not require rainproofing on pad, will utilize stronger materials than the orbiter, could be provided a low porosity surface by density grading or application of a surface sealer. If the current RSI coating mass could be reduced by 50%, a net reduction of 9% of TPS mass would occur. For a ground based AOTV, a customer cost benefit of $1.5M/flight would result for GEO delivery missions.
Objective:	To provide multicycle demonstration of sealed RSI operating at the higher allowable maximum operating temperatures.
Technical Approach:	Conduct a series of Plasma Arc Tests in simulated entry environments on the candidate AOTV TPS materials employing various surface densification/sealer techniques. Assume two new coating candidates per year for the next three years.
Resource Requirements:	Advocate continuation of on-going programs

	FY 86	87	88
Manpower (yrs)	1.5	1.5	1.5
Specialized Facilities	Plasm Arc Test Facilities		
Funding ($K)	200	200	200